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**Vortex Flow Visualization using Colored and
Fluorescent Dyes on a Flat Plate Delta Wing
with Leading Edge Extension**

A Water Tunnel Study

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FOREWORD

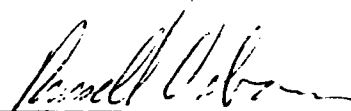
This report was prepared by Capt Scott P. LeMay of the Aerodynamics and Airframe Branch, Aeromechanics Division, Wright-Patterson AFB, Ohio 45433-6553. The work was performed in September 1989 under the work unit number 240410B2, Vortex Flow Technology.

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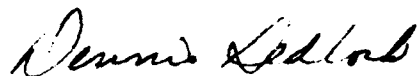
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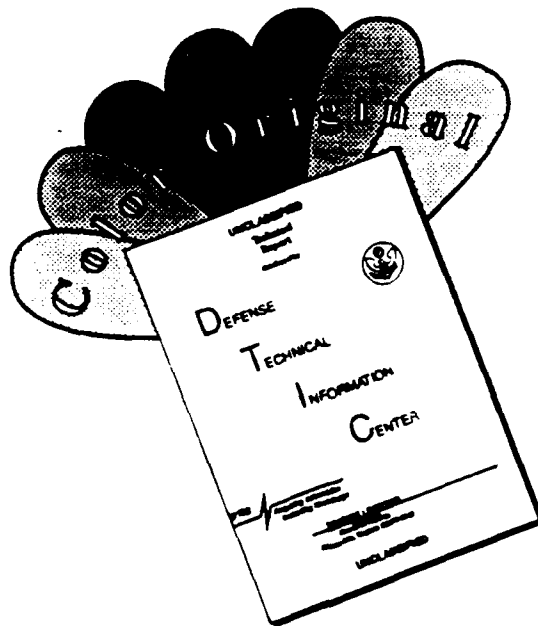


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ABSTRACT

A water tunnel study was conducted in the Wright Laboratory 2ft x 2ft water tunnel to examine the vortex flowfield about a 60° flat plate diamond delta wing with an 80° leading edge extension (LEX). Flood light illuminated colored dye and laser light sheet illuminated fluorescent dye were used to visualize the wing and LEX vortex core trajectories and vortex breakdown locations. The fluorescent dye flow visualization technique proved to be an excellent tool for examining the structure of vortex breakdown in detail. Angle of attack was varied between 10° and 45° for sideslip angles of 0°, 5°, and 10°, and the freestream Reynolds number was approximately 31,000 based upon model length. At angles of attack above 10° and zero sideslip, interaction was observed between the LEX and wing vortices. At 30° angle of attack, asymmetric breakdown of the LEX vortices occurred. At sideslip angles of 5° and 10°, large asymmetries in the vortex flowfield were present.



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INTRODUCTION

The high angle of attack flowfields about advanced fighter aircraft are dominated by separated vortical flows. The vortical flowfields generated by the wing, leading edge extensions (LEXs), and forebody can often interact with one another promoting non-linear effects on the aerodynamic stability and control characteristics (Reference 1). Other problems encountered are destabilizing "pitch-up" tendencies, caused by vortices being shed off the forebody, and zero beta yawing moments caused by asymmetric vortex shedding.

As modern fighter aircraft are expected to maneuver to these high angle of attack flight regimes, the investigation of the complex, separated, three-dimensional flowfields through either experimental, flight, or analytical means becomes increasing more important because of the aforementioned associated problems.

This technical memorandum documents the results of a water tunnel study in which the vortex flowfield about a flat plate delta wing incorporating a highly swept LEX is investigated. Not only is the vortex flowfield about the delta wing investigated, but a unique flowfield visualization technique is presented which incorporates the use of fluorescent dyes which are illuminated by a sheet of laser light. This technique allows for detailed study of the vortex core structure and breakdown region.

EXPERIMENTAL APPARATUS and DATA ACQUISITION

Water Tunnel

The Wright Laboratory (WL) 2ft x 2ft Water Tunnel (Figure 1) is a continuous gravity flow, atmospheric, hydrodynamic facility which has a maximum test section velocity of 0.85 ft/sec. Optimum dye flow visualization velocities range from 0.10 to 0.30 ft/sec. The test section is 2ft x 2ft and has a length of 4ft. Two inch thick Plexiglas windows are located on two of the sides of the test section to allow for plan view and side view observations. A third side has a slide away door which allows for access to the test section.

The tunnel reservoir is supplied with softened water by a 3600 gpm, 120 ft head, centrifugal, recirculating pump which draws water from two 6400 gallon stainless steel storage tanks. The water is pumped through piping to a slotted inlet manifold located around the inside perimeter of the reservoir approximately 10 ft above the tunnel throat. An 8 inch thick, open-celled, polyfoam, flow restrictor is suspended beneath the inlet manifold at the entrance to the contraction cone to reduce the turbulence intensity. Additionally, a hex-celled aluminum honeycomb flow straightener with an L/D of 8.0 is located just above the test section to improve flow quality.

The tunnel flow rate is controlled by an air operated control valve located in the discharge piping. The test section velocity is set using a Cox turbine flow meter which measures volumetric flow rate. For more information consult Reference 2.

Model

The model used in this experiment is a flat plate double-delta with a diamond planform wing and LEX (leading edge extension) and is shown in Figure 2. The model is made of aluminum and has a thickness of 0.125 inches. The main wing leading and trailing edge sweep angles are 60° and 30° respectively, and the LEX sweep angle is 80° . All edges are sharply beveled at 45° from the bottom surface to ensure a fixed separation point. The wing aspect ratio is 1.7 and its span is 9 inches. The planform area of the LEX is approximately 18 percent that of the main wing.

The model was mounted in the water tunnel using a centerline sting attached to the model undersurface in order to minimize interference effects.

Flow Visualization and Data Acquisition

Both colored and fluorescent dyes were used for flow visualization. A schematic of the dye injection system is shown in Figure 3. Dye was forced from a containment reservoir to the model using compressed air. The rate of

dye bleed was controlled by adjusting the pressure in the compressed air supply line. Fine adjustments to the dye flow rate were made with a needle valve located downstream of the containment reservoir. Electric solenoid valves were used to toggle the dye taps, and each could be operated independently. Four dye taps were used in the present experiment to bring dye to the apex region of the LEX and the LEX/wing junctions.

All data taken were qualitative in nature and obtained solely from visual observations. Three-quarter inch video tape, and 50mm and 35mm still photography were used to record the data. The video taped data were used to record the dynamics of the vortex flowfield and the still photography to provide a medium on which to report documentable information. Normal floodlight illumination was used to visualize the colored dyes.

In the fluorescent dye cases, however, a sheet of laser light was used to fluoresce the dye. The laser light sheet made it possible to obtain "cross-cuts" of the vortex flowfield, providing a means for examining the vortex structure in detail. Both longitudinal and perpendicular cross-cuts were obtained. In this memorandum only longitudinal cross-cuts are presented.

The laser light sheet was generated by passing the laser beam from a 5-watt argon-ion laser through a cylindrical lens. The laser light contained eight bands of light consisting of wavelengths from 460nm (blue) to 550nm (green). The dye used for the laser light sheet visualization was rhodamine

G which fluoresced bright yellow when excited by the laser. The laser light was filtered out of the photographic and video taped data using a special lens leaving only the fluorescent light for the photographic exposure.

RESULTS and DISCUSSION

Colored Dye Flow Visualization

Colored dye flow visualization data were acquired at angles of attack between 10° and 45° for sideslip angles (β) of 0° , 5° , and 10° . In the data presented, red dye was used to visualize the LEX vortices and blue dye was used to visualize the wing leading edge vortices.

In Figure 4, a sequence of planform photographs is presented for increasing angle of attack at zero degrees sideslip. At 10° angle of attack (Figure 4a) the flow is separated along the entire length of the LEX and wing due to the sharpness of the leading edges. The LEX vortices (red) appear weak and are ill-defined. The wing vortices (blue) are more clearly defined, and at approximately mid-wing begin interacting with the LEX vortices. This interaction or coupling of the LEX and wing vortices has been noted by Hall (Reference 3) and LeMay (Reference 4) to delay breakdown at lower angles of attack. However, this interaction has also been found to promote undesirable lateral-directional stability and control characteristics such as nose-slicing and roll divergence. At 20° angle of attack (Figure 4b) the LEX vortices are more clearly defined and dominate

the wing vortices which are drawn into the co-rotating LEX vortex system to form a closely knit pair. At this angle of attack the wing or LEX vortices do not breakdown.

At 30° degrees angle of attack (Figure 4c) the wing vortices are broken down. Here, the wing dye (blue) is not used so that the LEX vortices are not obscured. Breakdown of the LEX vortices is asymmetric and occurs near the trailing edge of the wing. Asymmetric breakdown of the LEX vortices occurs at all angles of attack greater than 30°. This asymmetry is not uncommon for a sweep angle of 80° (Reference 5) and is caused by the close proximity of LEX vortices to one another.

At 40° degrees angle of attack (Figure 4e) the position of breakdown for the asymmetric LEX vortices is at a more forward location on the model and moves towards the apex with increasing angle of attack. At this angle of attack the vortex asymmetry oscillates from one side to the other. This oscillation occurs at no dominant frequency and appears to be random or chaotic, favoring neither one side or the other. A possible explanation for this oscillating asymmetry is that small instabilities in the flowfield, caused by model motion or freestream turbulence, might dictate which side of the model is favored.

At the highest angle of attack of 45° (Figure 4f) the breakdown position of the LEX vortices is much closer to the apex and there are large areas of separated and reverse flow over the main wing. The oscillation in

the vortex breakdown asymmetry occurs at this angle of attack as well. Note that in the photographs presented the model appears to get smaller with increasing angle of attack. The illusion is created because the camera is fixed and does not remain perpendicular to the model as angle of attack varies.

Fluorescent Dye Flow Visualization

Fluorescent dye flow visualization data were taken at angles of attack of between 10° and 45° for sideslip angles of 0° , 5° , and 10° . Only one color of fluorescent dye (yellow) was used to visualize the wing and LEX vortices.

In Figure 5, a sequence of planform photographs is presented for increasing angle of attack and zero degrees sideslip. The laser light sheet cross-cut through the plane of the vortices as shown in the photographs provides valuable insight into the detailed structure of the vortex cores and breakdown regions.

In Figure 5a, $\alpha = 10^\circ$, both the wing and LEX dye ports are used to visualize the vortex flowfield. The fluorescent dye flow visualization vividly illustrates the weak structure of the LEX vortices, with the "streaks of light" indicating a partially attached and partially separated flowfield. At $\alpha = 10^\circ$, the LEX vortices are just beginning to form, and the wing vortices are seen to quickly interact with the LEX vortices. Again, as

in the colored dye cases, the wing vortex dye taps were not used at the higher angles of attack so as to not obscure the visualization of the LEX vortices. At 20° angle of attack (Figure 5b), the LEX vortices are more clearly defined and do not breakdown. At $\alpha = 30^\circ$ (Figure 5c), asymmetric breakdown of the LEX vortices occurs near the trailing edge of the model.

Shown in figures 5d, 5e, and 5f are photographs taken of the model at 40° angle of attack. The photos show how the LEX vortex flow asymmetry oscillates from side to side as described in the previous section. Also visualized is the "spiral" nature of the LEX vortex breakdown (Reference 5) and highly turbulent structure of the vortex wake.

The laser light sheet fluorescent cross-cuts provide an excellent means with which to track the spiral breakdown of the LEX vortices into large scale turbulence. After the vortices begin to "corkscrew" they remain in a tight vortex spiral for up to 1.5 revolutions before the structure begins to break apart, at which time the vortex structure expands and axial velocity decreases. This spiral pattern can be seen in the wake of the broken down vortex for several revolutions. In the center of the broken down vortex wake are large regions of reverse flow. At 45° angle of attack (Figures 5g and 5h), the spiral pattern in the vortex wake can also be seen.

As the vortices propagate downstream the spiralling wakes sometimes interact constructively like teeth on a cogwheel, and at other times act destructively and butt up against one other. This varies with time, similar

to the oscillation in the breakdown location of the vortex asymmetry. Hence, the way in which the vortex wakes interact might possibly contribute to the oscillation of the observed vortex asymmetry.

Vortex Flowfield at Sideslip Condition

In Figure 6 two colored dye and two fluorescent dye photographs are presented for sideslip angles of 5° and 10° , and 35° angle of attack. At $\beta = 5^\circ$ and $\alpha = 35^\circ$ a large asymmetry in the flowfield exists (Figures 6a and 6c). Vortex breakdown occurs much farther upstream on the windward side than on the leeward side. This result was expected due to the effective decrease in the wing leading edge sweep angle on the windward side and increase on the leeward side.

At $\beta = 10^\circ$ and $\alpha = 35^\circ$ (Figures 6b and 6d) the asymmetry in the LEX vortex breakdown locations is more pronounced. At this condition the wing vortex (blue dye) interacts with the LEX vortex on the leeward side. This is similar to the $\beta = 0^\circ$ case at low alpha, except that vortex breakdown occurs farther downstream.

The laser light sheet photos indicate that breakdown of the LEX vortices is of the "spiral" type, and that the wake of the broken down vortex is structured the same as in the zero degrees sideslip case.

Conclusions

An experimental investigation was conducted in the Air Force Wright Laboratory 2ft x 2ft Water Tunnel to examine the vortex flowfield about a 60° flat plate diamond delta wing with an 80° Leading Edge Extension (LEX). Both flood light illuminated colored dye and laser light sheet illuminated fluorescent dye were used to visualize the flowfield. The conclusions are as follows:

1) At $\alpha = 10^\circ$ and $\beta = 0^\circ$ the vortex flowfield was separated along the entire length of the main wing and LEX, and the wing and LEX vortex interaction was observed at approximately mid-wing. This interaction continued throughout the entire angle of attack range of $\alpha = 10^\circ$ to 45° .

2) At $\alpha = 30^\circ$ asymmetric breakdown of the LEX vortices occurred near the trailing edge, and the wing vortices were broken down. As the angle of attack increased the position at which LEX vortex breakdown occurred moved toward the apex of the model. Asymmetric breakdown of the LEX vortices continued up to 45° angle of attack.

3) At $\alpha = 40^\circ$, an oscillation from side to side in the LEX vortex breakdown asymmetry was observed. This oscillation transpired at no apparent dominant frequency.

4) Laser light sheet fluorescent dye flow visualization proved to be an excellent tool for examining in detail the structure of vortex breakdown and the resulting wake of the burst vortex. The dye flow data revealed that the characteristic of vortex breakdown was "spiral" in fashion for both the

zero and non-zero sideslip cases, and that after breakdown the vortex wake retained this spiral pattern. Data also revealed that a large area of reverse flow exist in the center of the burst vortex wake.

5) At $\alpha = 35^\circ$, large asymmetric flow patterns were observed at sideslip angles of 5° and 10° . In both cases the LEX vortex on the windward side broke down forward of the wing/LEX juncture, while the LEX vortex on the leeward side did not breakdown until well past the trailing edge of the main wing.

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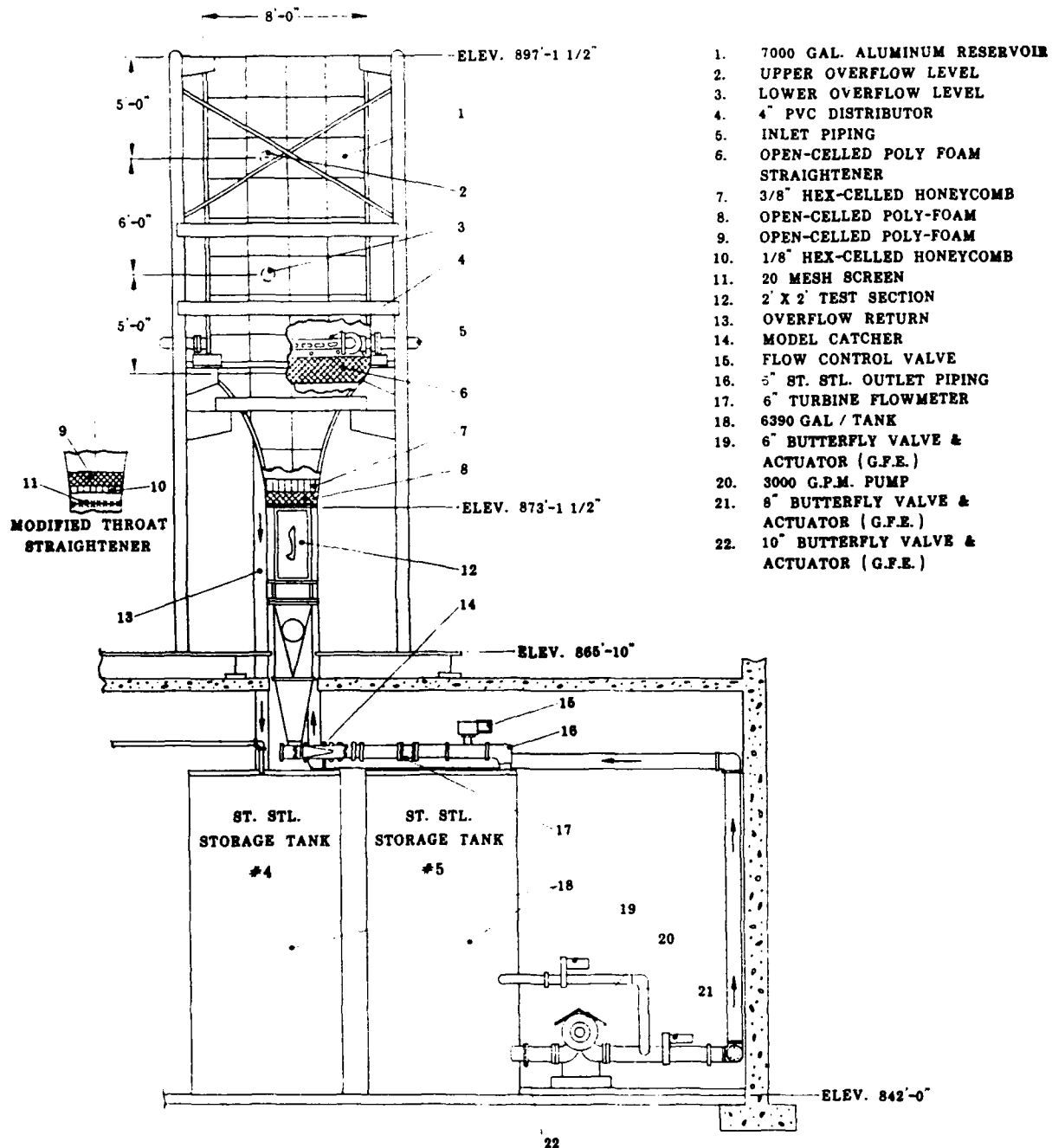


Figure 1: Wright Laboratory 2ft x 2ft Water Tunnel.

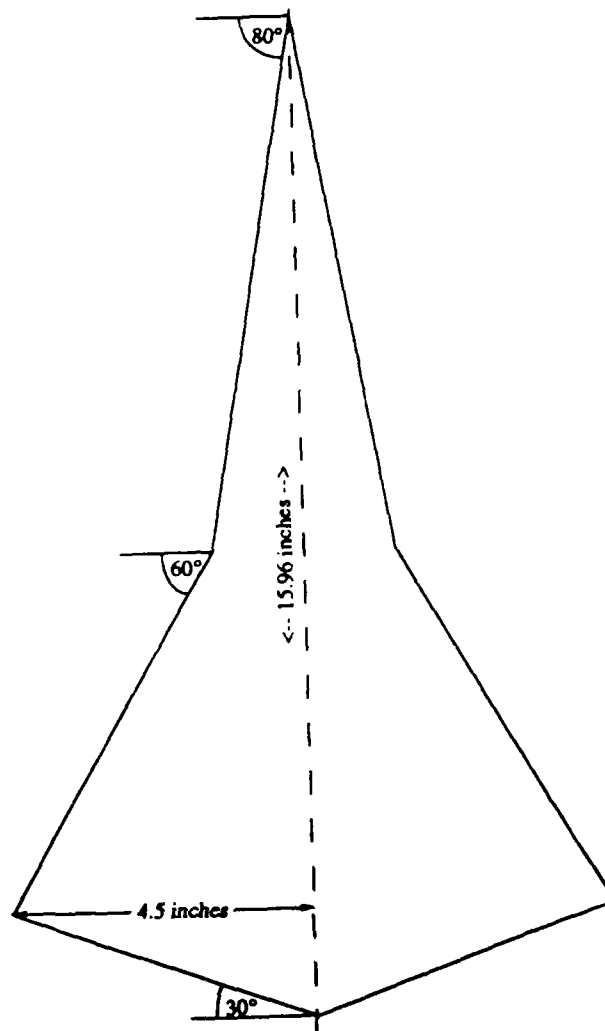


Figure 2: Flat Plate Diamond Delta Wing with Leading Edge Extension.

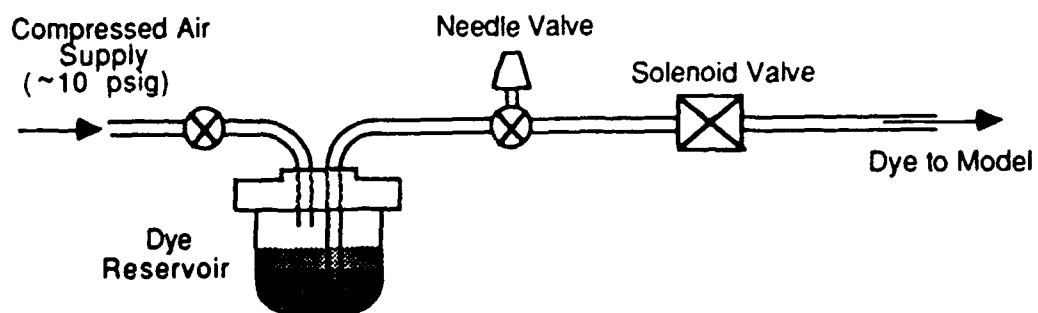
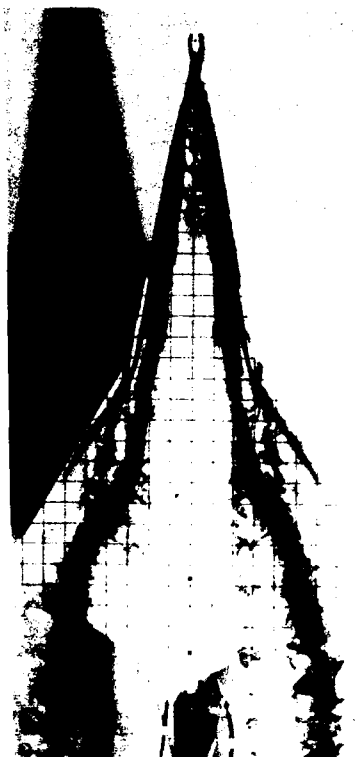
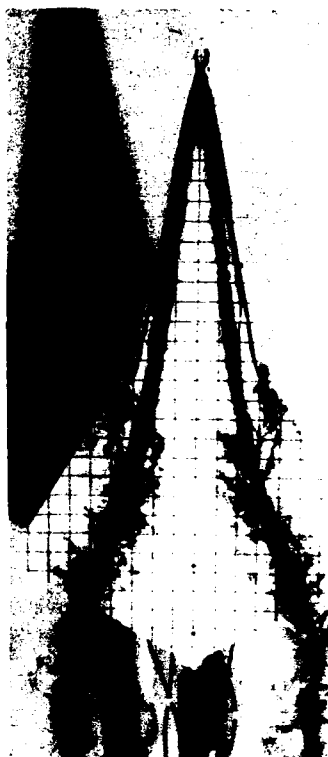


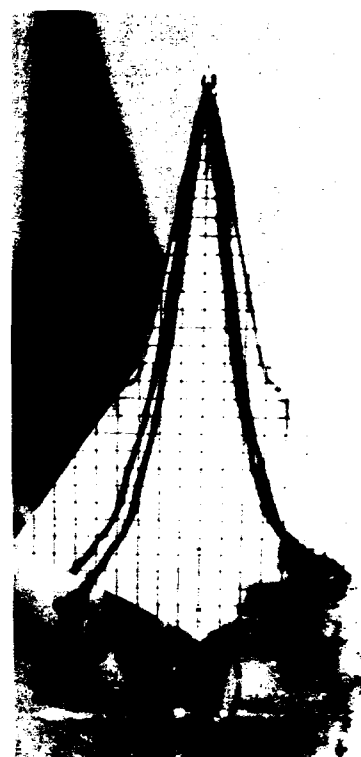
Figure 3: Dye Injection System.



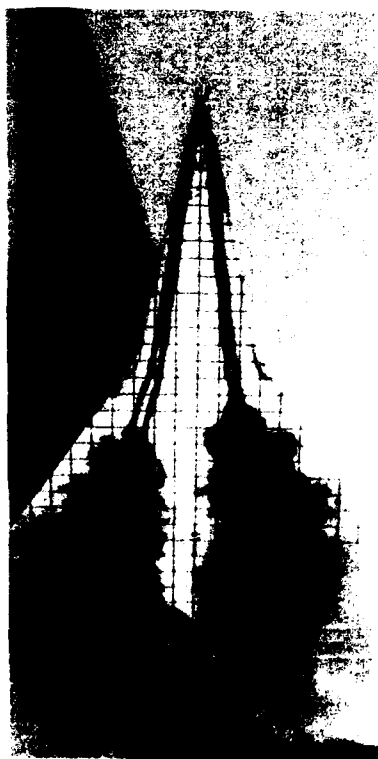
4a) $\alpha = 10^\circ$



4b) $\alpha = 20^\circ$



4c) $\alpha = 30^\circ$



4d) $\alpha = 35^\circ$

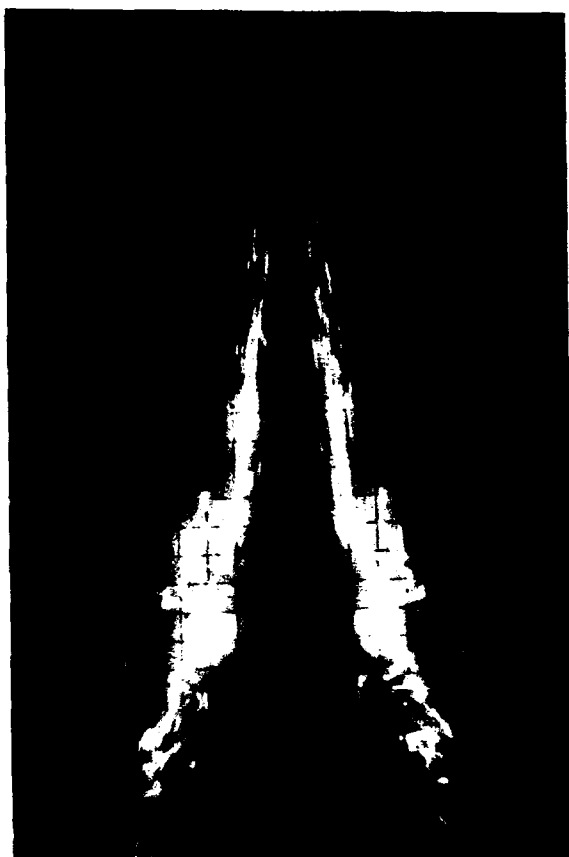


4e) $\alpha = 40^\circ$



4f) $\alpha = 45^\circ$

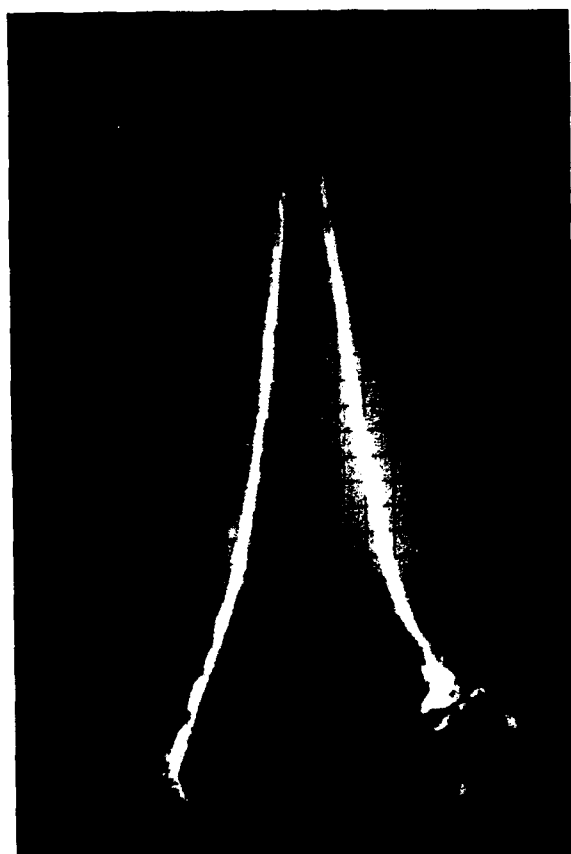
Figure 4: Colored Dye Flow Visualization, $\alpha = 10^\circ$ to 45° , $\beta = 0^\circ$.



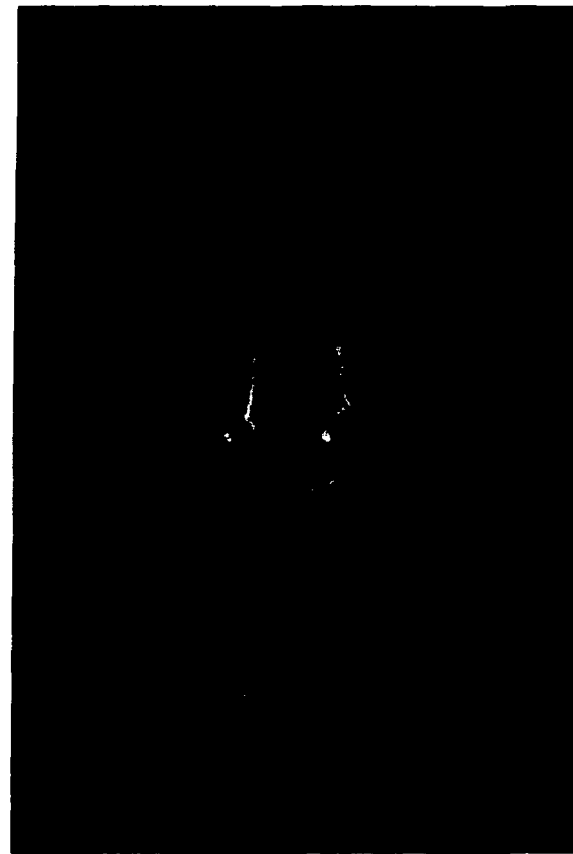
5a) $\alpha = 10^\circ$



5b) $\alpha = 20^\circ$

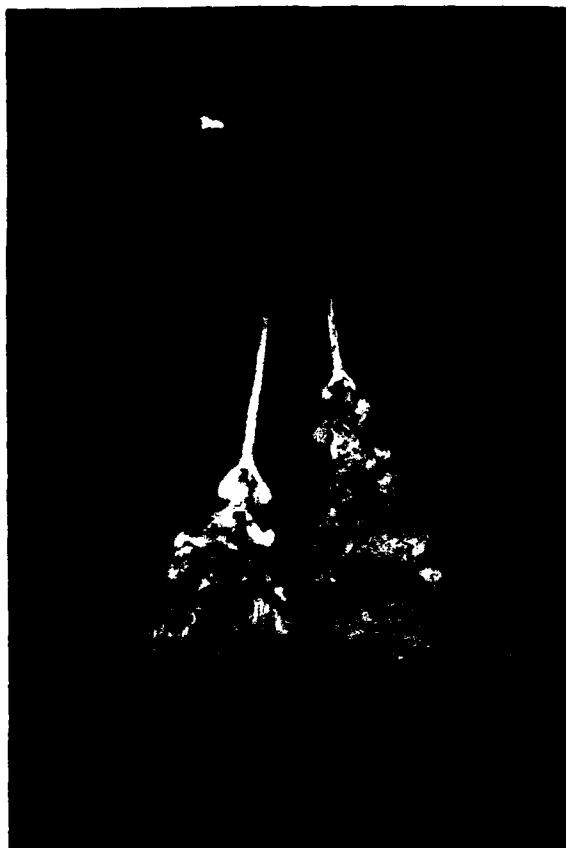


5c) $\alpha = 30^\circ$

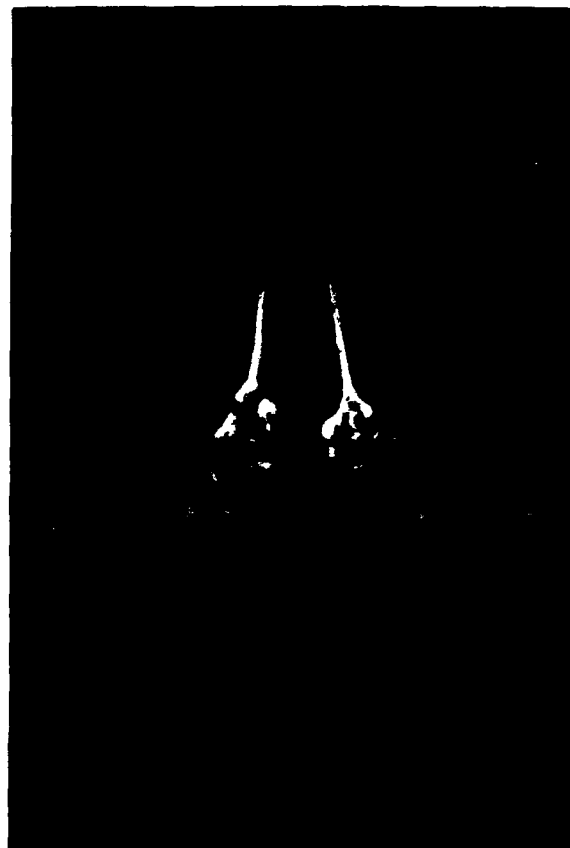


5d) $\alpha = 40^\circ$

Figure 5: Fluorescent Dye Flow Visualization, $\alpha = 10^\circ$ to 45° , $\beta = 0^\circ$.



5e) $\alpha = 40^\circ$



5f) $\alpha = 40^\circ$



5g) $\alpha = 45^\circ$



5h) $\alpha = 45^\circ$

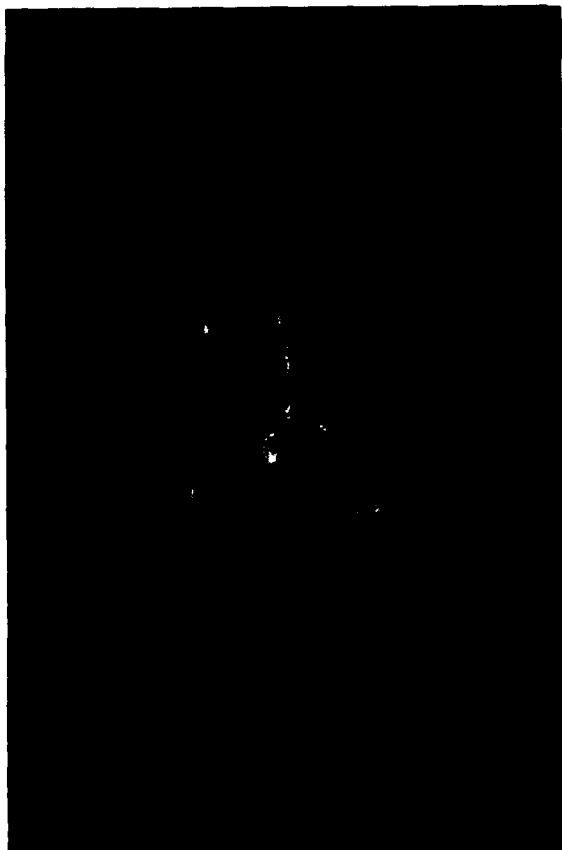
Figure 5 continued.



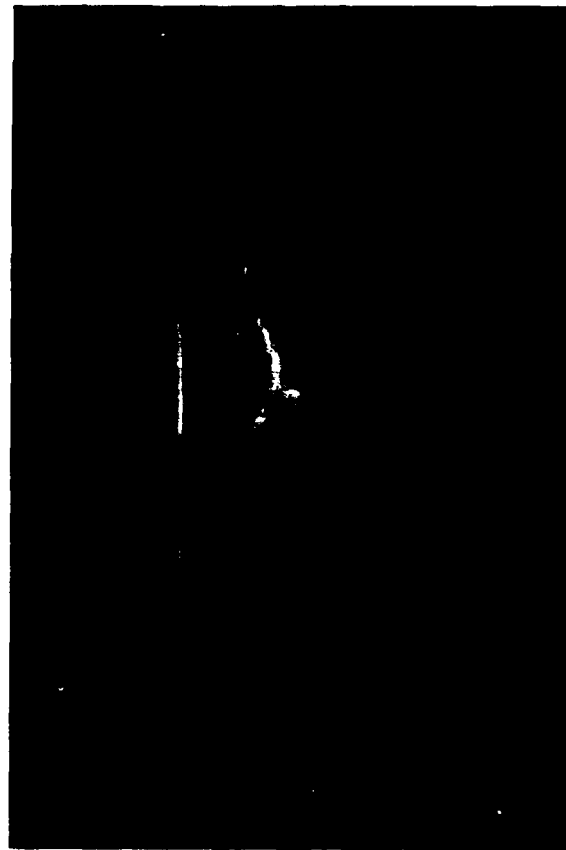
6a) $\alpha = 35^\circ$, $\beta = 5^\circ$



6b) $\alpha = 35^\circ$, $\beta = 10^\circ$



6c) $\alpha = 35^\circ$, $\beta = 5^\circ$



6d) $\alpha = 35^\circ$, $\beta = 10^\circ$

Figure 6: Flow Visualization at Sideslip, $\alpha = 35^\circ$, $\beta = 5^\circ$ and 10° .